Asian Agricultural Research 2014, 6(4): 79 – 84

Composite Simulation of Dynamic Water Content and Water Use Efficiency of Winter Wheat

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Abstract In order to forecast the effect of climate warming on agriculture, ENWATBAL model was used to simulate evapotranspiration of winter wheat due to the change of air temperature and precipitation in the coming decades. The effect of climate warming on winter wheat yield in the future decades was speculated by the past yield and climate data in last decades, and the possible water use efficiency in the future decades was calculated. The results indicate that climate warming would increase winter wheat evapotranspiration, and decrease yield and water use efficiency of winter wheat. It shows that climate warming would intensify the water shortage in agriculture, and it is necessary to develop water-saving agriculture.

Key words Winter wheat, Climate warming, ENWATBAL model, Water use efficiency

In recent years, global warming trends are becoming evident, and for the arid and semi-arid areas as well as the countries with a large agricultural population, the impact of climate warming on agricultural production would be enormous. In accordance with the method of combining water balance and heat balance, Shi Yafeng[2] estimated the impact of climate change in the North China Plain on the local water resources: when there was 10% increase in precipitation, and the temperature was increased by 1 – 1.5 ℃, the evaporation capacity would also be increased by 10%. People are more concerned about whether the impact of climate warming on agricultural production is positive or negative.

For crops such as winter wheat, the higher temperature and increased precipitation will cause changes in evapotranspiration, and result in a corresponding change in water use efficiency. The water use efficiency is in general obtained by calculating the quotient of production and water utilization amount.

If we can use a model to input temperature, precipitation and other parameters, and directly simulate changes in crop evapotranspiration, then we can estimate the amount of water required by crops in the case of future climate warming. By using other functions, we estimate the crop yields and water use efficiency, thereby knowing the crop production and water utilization amount in the case of future changes in temperature, and establishing the rational agricultural production and irrigation methods.

Currently agricultural irrigation water is very tight, and a number of issues have occurred in many places such as ground subsidence and saltwater intrusion due to the extensive groundwater pumping for irrigation. These issues will worsen with the global warming. Some Chinese scholars such as Qiu Guiyu *et al.*[3], Zhang Xiying *et al.*[4] and Zhang Yongqiang *et al.*[5] have made some studies and presented reasonable irrigation schemes on reasonable water-saving irrigation for winter wheat and other crops.

However, there are rare studies on the relationship between climate change and the crop evapotranspiration over a long time. Therefore, with the major food crop winter wheat in the North China Plain as the object of study, based on the historical data and the composite simulation of ENWATBAL model, this article explores the impact of long-term climate change on the winter wheat yield and water use efficiency, to provide a basis for the study of agricultural water conservation.

1 ENWATBAL model

1.1 Description of the model ENWATBAL (Energy & Water Balance) model is a large dynamic mechanism model using the function of crop growth conditions, soil conditions and weather factors, to calculate crop transpiration and soil evaporation in the soil – crop – atmosphere continuum and other relevant water content and energy balance parameters on the crop and soil interface, respectively.

This model was proposed by Lascan *et al.*[6] on the basis of CONSERVB model[7], WATBAL model[8] and MICROWEATHER model[9–10], and was applied first to cotton and sorghum[6, 11–14] grown in the sandy loam and corn and winter wheat planted in clay loam[15–16] in Texas of the United States and then to sorghum planted in the coarse sand soil in Tottori of Japan[17–19].

The results in the above regions have proved that the model can accurately estimate the soil evaporation and plant transpiration. There is not any example of validation and application at home. ENWATBAL is not the crop growth model, but it can predict the soil water content conditions and temperature, so it can be used to investigate emergence and irrigation seasons closely related to soil water content and temperature.

In the model, the soil section is divided into several layers, and the closer to the surface layer, the smaller the thickness. Soil moisture flux is calculated using Darcy's law, and the boundary

Received: December 16, 2013 Accepted: February 28, 2014
Supported by Financial Aid of Beijing City (PXM2012_014202_000193).
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conditions of the lower soil can be defined as the unit gradient flow rate based on the current water potential. When the precipitation is less than the infiltration capacity of the upper soil, the upper boundary condition of water flux is the precipitation rate, otherwise the boundary condition is the water depth.

Soil infiltration capacity (INCAP) is calculated as follows:

$$INCAP = -HPOT_1 \times [(SATCON + COND_1)/2] \times DIST_1$$

where $HOPT_1$ is the top soil water potential (m); *SATCON* is the top soil saturated hydraulic conductivity (m/s); $COND_1$ is the top soil hydraulic conductivity in the current soil water potential (m/s); $DIST_1$ is the distance between the soil surface and the middle of top soil.

Based on Fourier's law, soil heat flux is calculated using the thermal conductivity corrected by vapor flux. The boundary condition of lower soil heat flux is a constant temperature, given by the program appliers in the initial soil moisture and temperature conditions.

The boundary condition of upper soil heat flux (including latent heat flux) is calculated by the following energy balance equations:

$$LWRS = \sigma \times (TS + 273.16)^4$$

$$NEBS = GR \times ABSS\alpha + (1 - FTSR) \times LWRC + FTSR \times SKL - LWRS$$

$$HO = 1.323 \times exp[17.27 \times TS/(237.3 + TS)]/(273.16 + T_S)$$

$$HS = HO \times exp\{PPOT_1/[46.97 \times (TS + 273.16)]\}$$

$$LEVS = (H_S - H_A) \times LH/RS$$

$$A = (T_S\text{-}t_A) \times SH/RS$$

$$S = NRBS\text{-}a - LEVS$$

$$0 = (T_S\text{-}tEMP_1) \times (KOND1/DIST_1)\text{-}s$$

where *LWRS* is soil longwave radiation [J/(s · m^2)]; σ is Stefan-Boltzmann constant [$\sigma = 5.67 \times 10^{-8}$ J/(m · K^4 · s)]; T_s is the soil surface temperature (℃); *NEBS* is soil surface net radiation balance [J/(s · m^2)]; *GR* is solar shortwave radiation [J/(s · m^2)]; *ABSSα* is the soil absorption rate; *FTSR* is the canopy transmittance rate; *LWRC* is the canopy longwave radiation [J/(s · m^2)]; *SKL* is the sky longwave radiation [J/(s · m^2)]; *HO* is the potential moisture under the soil surface temperature (kg/m^3); *HS* is the topsoil actual humidity (kg/m^3); $PPOT_1$ is the topsoil water potential (m); *LEVS* is the latent heat flux between soil and air [J/(s · m^2)]; *HA* is the absolute air humidity (kg/m^3); *LH* is the latent heat of water vapor (J/kg); *RS* is the aerodynamic resistance (s/m); *A* is the sensible heat flux between soil and air [J/(s · m^2)]; *TA* is the air temperature (℃); *SH* is air heat capacity [(J/(m^3 · ℃)]; *S* is the soil heat flux [J/(s · m^2)]; $TEMP_1$ is the topsoil temperature (℃); $KOND_1$ is the topsoil thermal conductivity [J/(s · m · ℃)]; $DIST_1$ is the distance between the soil surface and the middle of top soil.

The boundary conditions of plant canopy are determined by the following equations based on the theory of energy balance:

$$LWRC = \sigma \times (TL + 273.16)^4$$

$$NRBC = GR \times ABSC + (1 - FTSR) \times (SKL - LWRS)$$

$$HL = 1.323 \times exp[17.27 \times TL/(237.3 + TL)]/(273.16 + TL)$$

$$LTR = (HL - HA) \times LH/CRV$$

$$SHCA = LTR - NRBC$$

$$0 = (TA\text{-}tL) \times SH/CRH\text{-}sHCA$$

where *LWRC* is canopy longwave radiation [J/(s · m^2)]; NRBC is the canopy net longwave radiation [J/(s · m^2)]; ABSC is the canopy absorption rate; HL is the leaf absolute humidity (kg/m^3); TL is the leaf temperature (℃); LTR is the transpiration rate [J/(s · m^2)]; CRV is the latent heat flux resistance (s/m); SHCA is canopy-air sensible heat transfer [J/(s · m^2)]; CRH is disturbance resistance (s/m).

The energy water content balance equation of canopy and soil is as follows:

$$CL1 = f(WPOTCR)$$

$$CL = 2/(CL1 - 1 + CL2 - 1)$$

$$RL = CL - 1 \times LAI - 1$$

$$CRV = CRH + RL$$

$$LTR = (HL - HA) \times LH/CRV$$

$$0 = (WPSEFF + WPCRMX - WPOTCR) \times (1000 \times LH) \times (LAI/SRCR) - LTR$$

where CL1 is the skin conductance based on canopy water potential (m/s); WPOTCR is the canopy water potential (m); CL is the total skin conductance (m/s); CL2 is the skin conductance based on solar radiation (m/s); RL is the canopy stomatal resistance (s/m); CRV is the latent heat flux resistance (s/m); WPSEFF is the effective soil water potential (m); WPCRMX is the maximum canopy water potential (m).

This model is not a crop growth model, so there is a need to input three vegetation parameters (leaf area index, root depth and maximum root length density).

Leaf area index is used to calculate disturbance resistance between canopy and air, between soil and air, the canopy-soil optical characteristics, and the root water absorption capacity.

Root parameters are used to calculate the effective soil water potential of root and root water absorption capacity.

1.2 Input and output of the model The parameters needed to be input for ENWATBAL model include three groups, soil parameters, vegetation parameters and meteorological parameters, added as required to several sub-files of model[20], as shown in Table 1[20].

The model can be used to calculate and output a series of parameters related to soil, vegetation and air, as shown in Table 2.

2 ENWATBAL model validation

Using the meteorological data, vegetation parameters and soil data on the winter wheat planted in the large evapotranspiration meter in the spring of 2005, we input them to ENWATBAL model and run the model, and then carry out comparative analysis of the simulation results and the measured data of the large evapotranspiration meter.

In order to verify the applicability of the model, we calculate the mean absolute error (MAE) between simulated values and measured values[21-22].

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|S_i - M_i|$$

where S_i and M_i are the simulated values and measured values, respectively; N is the number of data groups.

Table 1 Input parameter file of ENWATBAL model

File name	File description
ENWATBAL. FIL	Including the name and description of other documents, start and end time of the simulation model, output mode of the simulation results, etc.
INIT. *	Simulating the soil conditions at the start and end time (soil depth of various layers, soil moisture, soil temperature); * is the start and end time.
IRR – PREC. *	Daily irrigation and rainfall during the simulation; * is the year of the model simulation
ENWATBAL. *	Daily meteorological data and vegetation data during simulation; * is the year of the model simulation
ENWATBAL. CON	Parameters used for the model
ENWATBAL. FGN	Data table required for the model equations
WP. DAT	Half-hour weather data

Table 2 Output parameters of ENWATBAL model

Data set	Specific parameters
Temperature	Leaf temperature, soil surface temperature, the average temperature of the top layer of soil
Conductivity	Leaf skin conductance, leaf skin conductance generated by leaf water potential, leaf skin conductance generated by solar radiation
Resistance	Leaf skin resistance, sensible heat canopy flux resistance and latent flux canopy resistance per unit leaf area index
Humidity	Internal absolute humidity of leaf, absolute humidity of air, soil surface saturated humidity, average absolute humidity of topsoil
Flux 1	Sky longwave radiation, net radiation balance of crops, soil net radiation balance, crop longwave radiation, soil reflectance
Flux 2	The sensible heat flux between canopy and air, soil longwave radiation, soil evaporation flux, sensible heat flux between soil and air, soil surface heat flux, and canopy transpiration
Potential	Effective soil water potential, crop potential, the average water potential of topsoil
Plant parameters	Leaf area index, view factor, crop shortwave absorption capacity, not including the sensible heat flux canopy resistance of aerodynamic resistance, not including topsoil resistance of aerodynamic resistance
Evapotranspiration	Soil evaporation, canopy transpiration, evapotranspiration, soil heat flux, infiltration, deep drainage, runoff, water balance, root water uplift
Section	Soil water content section, soil temperature section

2.1 Comparison of simulated and measured values of daily evapotranspiration of winter wheat field In Fig. 1, the simulated values are the data of 53 days. Due to a few days of power outage or precipitation, it leads to the missing of large evapotranspiration meter data, and there are the data of 42 days.

There is good consistency between simulated values and measured values of daily evapotranspiration, and the correlation coefficient $r^2 = 0.719$, and the mean absolute error between the two $MAE = 0.86$ mm/day. The 42 days of total evapotranspiration measured is 268.04 mm, while the 42 days of total evapotranspiration simulated is 274.21 mm.

2.2 Comparison of the soil evaporation and transpiration values of winter wheat and the measured values of large evapotranspiration meter Fig. 2 is the comparison of simulated soil evaporation and transpiration values of winter wheat using ENWATBAL model and the measured soil evaporation and transpiration values of winter wheat using large evapotranspiration meter.

The simulated values are 52 days of data, and due to power outage or rain, some data are missing, and the measured values of soil evaporation and transpiration are 38 days of data and 32 days of data, respectively.

It can be found that the simulated values and measured values of soil evaporation are fitted well, the correlation coefficient between the two $r^2 = 0.885$, and the mean absolute error MAE = 0.13 mm/day. The 38 days of total simulated values of soil evaporation are 30.15 mm, while the simulated values are 26.27 mm.

In contrast, the fitting effect of transpiration is a little poor, the correlation coefficient $r^2 = 0.74$, and the mean absolute error MAE = 0.86 mm/day. The 38 days of total simulated values of transpiration are 175.57 mm, while the simulated values are 182.67 mm.

The density of the winter wheat planted in the evapotranspiration meter is slightly larger than the density of the winter wheat planted in farmland, and the leaf area index reached 6.28 – 7.25 during the simulation, so whether it is simulation or actual measurement, the proportion of soil evaporation to total evapotranspiration is relatively small, only about 13%. However, from the analysis of the simulation results, it proves that ENWATBAL model can be used to predict soil evaporation, plant transpiration and evapotranspiration of winter wheat field.

3 Simulating the response of winter wheat to regional climate change using ENWATBAL model

3.1 The impact of global climate change on North China's climate For the future trend of global climate change, the mainstream view of scientists at home and abroad in recent years is that the climate warming is caused by the greenhouse effect, and there will be some corresponding changes in the precipitation in different regions[1].

According to the study, the magnitude of China's global warming is slightly larger than the average magnitude of global warming, and especially in the winter, there is a small increase in the precipitation.

Relying on the subject "Climate Change, Climate Resources and Sustainable Development of the Country" of the Ministry of Science and Technology, Chen Zhixin *et al.*[23] studied the issues concerning the impact of the future climate change on sustainable agricultural development, and used GCM model to simulate every 10 years of climate change scenario from 2010 to 2050 in northern China (including the main winter wheat growing areas in North China) (see Table 3).

As can be seen from Table 3, the future magnitude of warming in winter is slightly higher than in other seasons; the rate of increase in precipitation is also higher in winter, but it is smaller than the magnitude of warming, leading to strong evaporation, and reduced soil water content. The changes in these climatic conditions will inevitably have an impact on the winter wheat yield.

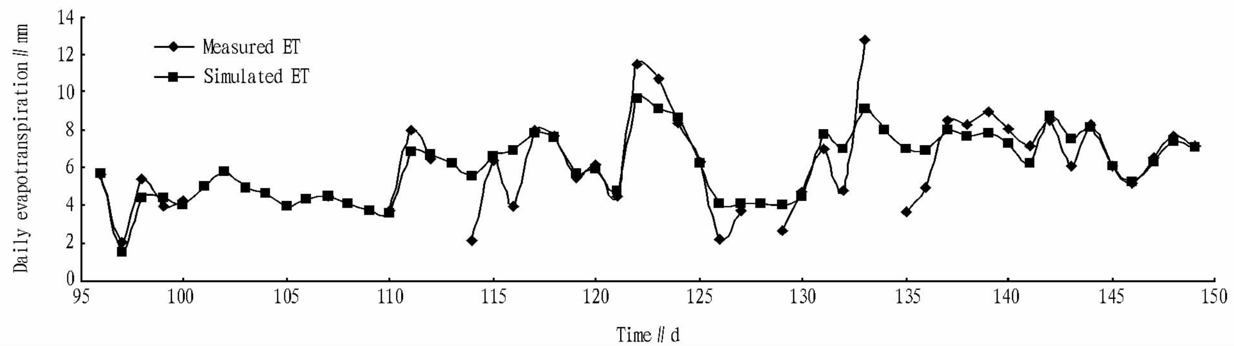

Fig. 1 Comparison of simulated values and measured values of daily evapotranspiration of winter wheat field

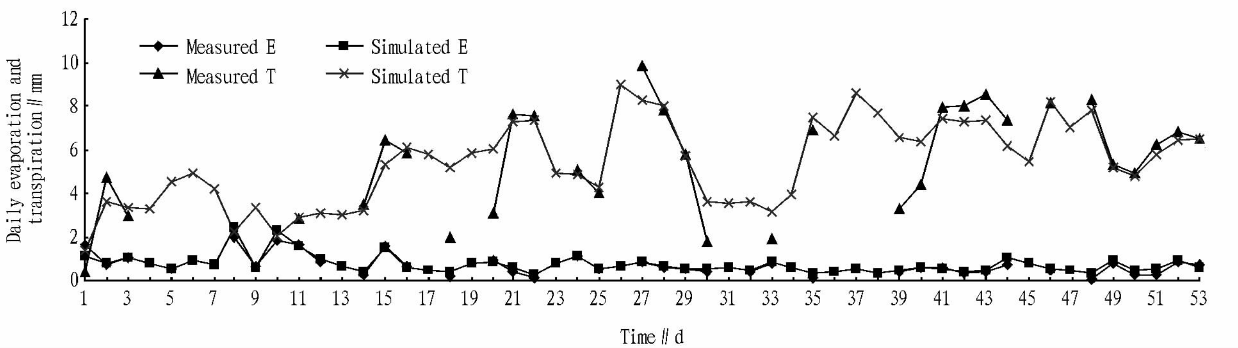

Fig. 2 Comparison of simulated soil evaporation and transpiration values of winter wheat and the measured soil evaporation and transpiration values of winter wheat

Table 3 The simulated climate change scenarios from 2010 to 2050 using GCM model

Year	Temperature changes // ℃					Precipitation changes // %				
	Winter	Spring	Summer	Autumn	The annual average	Winter	Spring	Summer	Autumn	The annual average
2010	0.38	0.35	0.34	0.35	0.35	1.4	1.3	1.2	0.9	1.1
2020	0.69	0.63	0.62	0.64	0.65	2.6	2.3	2.1	1.6	1.9
2030	0.93	0.86	0.84	0.87	0.88	3.5	3.2	2.8	2.2	2.6
2040	1.12	1.04	1.02	1.05	1.06	4.2	3.8	3.4	2.5	3.2
2050	1.48	1.37	1.34	1.38	1.40	5.5	5.1	4.5	3.5	4.2

3.2 The impact of climate change on winter wheat yield

Min Jinru[24] analyzed the impact of climate warming on the Chinese wheat production, and found that the rising temperature increased >0 ℃ accumulated temperature in the growth period of winter wheat in North China, reduced the frozen injury of winter wheat, and shortened the entire growth period, easily leading to insufficient grain filling; there will be a slight increase in the future precipitation of this region, not conducive to the growth of winter wheat, thereby leading to reduced production of winter wheat, which is the negative effect of climate warming on winter wheat yield.

However, in the process of global warming, the CO_2 warming effect can account for 65%, so other researchers[23] discussed the impact of the increased concentration of CO_2 on winter wheat growth, and believed that with the increased concentration of CO_2, the photorespiration energy consumption of winter wheat as C3 plant was reduced, and the photosynthetic rates were greatly improved, which was conducive to the synthesis and accumulation of dry matter; the temperature increase reduced the leaf stomatal conductance of winter wheat, reduced transpiration, reduced water loss and improved water use efficiency.

The warming shortens the growth period of winter wheat, but the magnitude of warming in winter is higher than in other seasons, the actual number of effective growth days of winter wheat is relatively increased. And the rising temperature and shortened growth period can make the winter wheat become mature in advance, thereby avoiding the hazard of frequent hot wind in the post-growth period of winter wheat in the North China Plain. These are the positive effects of climate warming on winter wheat yield.

When discussing the impact of climate change on winter wheat yield, it is necessary to consider a lot of aspects, and different scholars have different views and findings[25-28], so it remains to be further explored. The following fitting analysis of the impact of future climate change on winter wheat yield is only an exploratory study.

To take advantage of GCM model and other crop growth models to predict the winter wheat yield change under climate change, it requires a lot of parameters and data, and it is difficult to achieve.

Given that there are few studies on the effect of CO_2 concentration on optical radiation changes, this article only considers the impact of temperature and precipitation changes on winter wheat yield.

According to the winter wheat yield record sequence in Luancheng from 1974 to 2004, and the meteorological record sequence of local weather observation sites in the same period, the fitted relationship between winter wheat yield in Luancheng, and the accumulated temperature and precipitation in the growth period of wheat, is the following quadratic polynomial ($r^2 = 0.599$, significant degree $= 0.0519$):

$$Y = -33\,388.677\,3 + 40.243\,5\sum T + 4.222\,6\sum P - 0.009\,7\sum T^2 + 0.103\,4\sum P^2 - 0.015\,4\sum T\sum P$$

where Y is winter wheat yield (kg/hm^2); ΣT is the accumulated temperature in the growth period of winter wheat (℃); ΣP is the total precipitation in the growth period of winter wheat (mm).

Using the above formula combined with the temperature and precipitation changes in Table 3, this article predicts the winter wheat production in 2010, 2020, 2030, 2040 and 2050, and the results are 6 323.86, 6 428.09, 6 434.79, 6 392.42 and 6 203.42 kg/hm^2, respectively.

The average annual yield of winter wheat during previous 30 years was 6 227.23 kg/hm^2, and the average annual yield of winter wheat in the period 2000 – 2004 was 6532.2 kg/hm^2, therefore, the yield of winter wheat has a decreasing trend in the future decades in general, and the changes in temperature and precipitation have negative effects on the yield of winter wheat.

3.3 The impact of climate change on the evapotranspiration and water use efficiency of winter wheat field Using the data of temperature change in the coming decades in Table 3, the corresponding temperature parameters in ENWATBAL model are adjusted. The model only carries out the simulation at one certain stage of winter wheat growth period, and the precipitation distribution is uncertain at this stage, so it does not simulate the precipitation changes, and only adjust the temperature parameters according to the increase or decrease of daily temperature during this stage.

By running the model and simulating the evapotranspiration changes under appropriate conditions, the evapotranspiration of winter wheat field in 2010, 2020, 2030, 2040 and 2050, is derived at 360.46, 364.28, 375.21, 386.87, 391.75 mm, respectively. Based on the prediction results of winter wheat yield, the water use efficiency is calculated at 1.754, 1.764, 1.715, 1.652, and 1.584 mm, respectively.

It can be found that in the case of temperature increase in the future, the evapotranspiration of winter wheat field will also increase, while the yield has a decreasing trend, so water use efficiency also shows a general trend of decrease.

4 Conclusions and discussions

For the possible impact of climate change caused by global warming on the yield, evapotranspiration and water use efficiency of winter wheat, based on other scholars' prediction data on future climate change, this article uses historical data and ENWATBAL model to simulate the yield and evapotranspiration changes of winter wheat in the coming decades, and finally calculates the water use efficiency changes.

The resulting exploratory conclusion is as follows:

In the case of gradually increased temperature and increased precipitation in the future, the winter wheat yield will decline; the evapotranspiration of winter wheat field will increase, and water use efficiency shows a general trend of decrease.

The results show that as global warming intensifies, the winter wheat yield will decline, and the increasing water demand will greatly exacerbate the pressure on rural irrigation, so how to rationally irrigate and improve the water use efficiency to ensure the crop yields is an issue that must be considered for the current and future agricultural production.

Some foreign scholars once used ENWATBAL model to study the relationship among temperature, precipitation and crop evapotranspiration in other countries[6-19]. I use ENWATBAL model for the first time to carry out study with winter wheat in the North China Plain as the object.

Due to limited time, I only use one year of experimental data from the CAS Luancheng Experiment Station to simulate the model. The simulated values and measured values are fitted well during this simulation, and the correlation coefficient $r^2 = 0.885$, but some accidental factors can not be excluded. Therefore, the applicability of this model in the North China Plain needs further verification.

The historical data fitting method is used to simulate the relationship between climate change and winter wheat yield, and despite the difference in the research methods, the conclusion is basically the same as the findings of other scholars[26-28], that is, the winter wheat yield will decline with the rising temperature. However, this study is only for winter wheat in the North China Plain, and if possible, we need to study other food crops.

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cubic polynomial projection transformation model can reach 2-3 pixels, and the geometric correction accuracy based on quadratic polynomial projection transformation model and quadratic polynomial linear push-broom model is about 4 pixels; in the high mountain areas, the geometric correction accuracy based on linear push-broom model and projection transformation model is roughly equal, about 6 pixels.

So, the cubic polynomial projection transformation model has the highest geometric correction accuracy, and it can be regarded as the geometric correction model for BJ-1 panchromatic image of the Kingdom of Lesotho. It should be noted that since we can not get more accurate geometric correction reference image of the Kingdom of Lesotho, this article uses Google Earth high-resolution image as the reference image for geometric correction, and geometric errors of its own will to a certain extent affect the geometric correction accuracy.

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